Towards a quantitative perspective in Networks of Bio-inspired Processors (NBP)

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Outline

Introduction

- Complex and hard problems in computation
  - NP complete
- Methods and paradigms to solve these problems in an efficient way
  - Bio-inspired models based on formal languages
  - Discrete approximations

Bio-inspired computational models

- Inspired from the nature: How nature computes?
  - Efficiently
  - Distributed
  - Massively parallelism
  - In a real time
- First step:
  - Mathematical and computer science goals
  - After biological goals.

NBP model

- Networks of bio-inspired processors
  - Maturity
  - Solves NP complete problems
    - Polinomial time with lineal number of resorces
  - Efficiency
  - Extensibility
  - Simplicity

Estado del arte: NBP

Características y poder computacional :

- Universales y computacionalmente completas
  - Resuelven problemas NP-completos
- Eficientes
  - Complejidad espacial: Número lineal de recursos
  - Complejidad temporal: polinomial
- Simples y Expresivas
- Extensibles / Escalables
- Distribuidas y paralelas

NBP model

Networks of bio-inspired processors – NBP [Mitrana,2001].

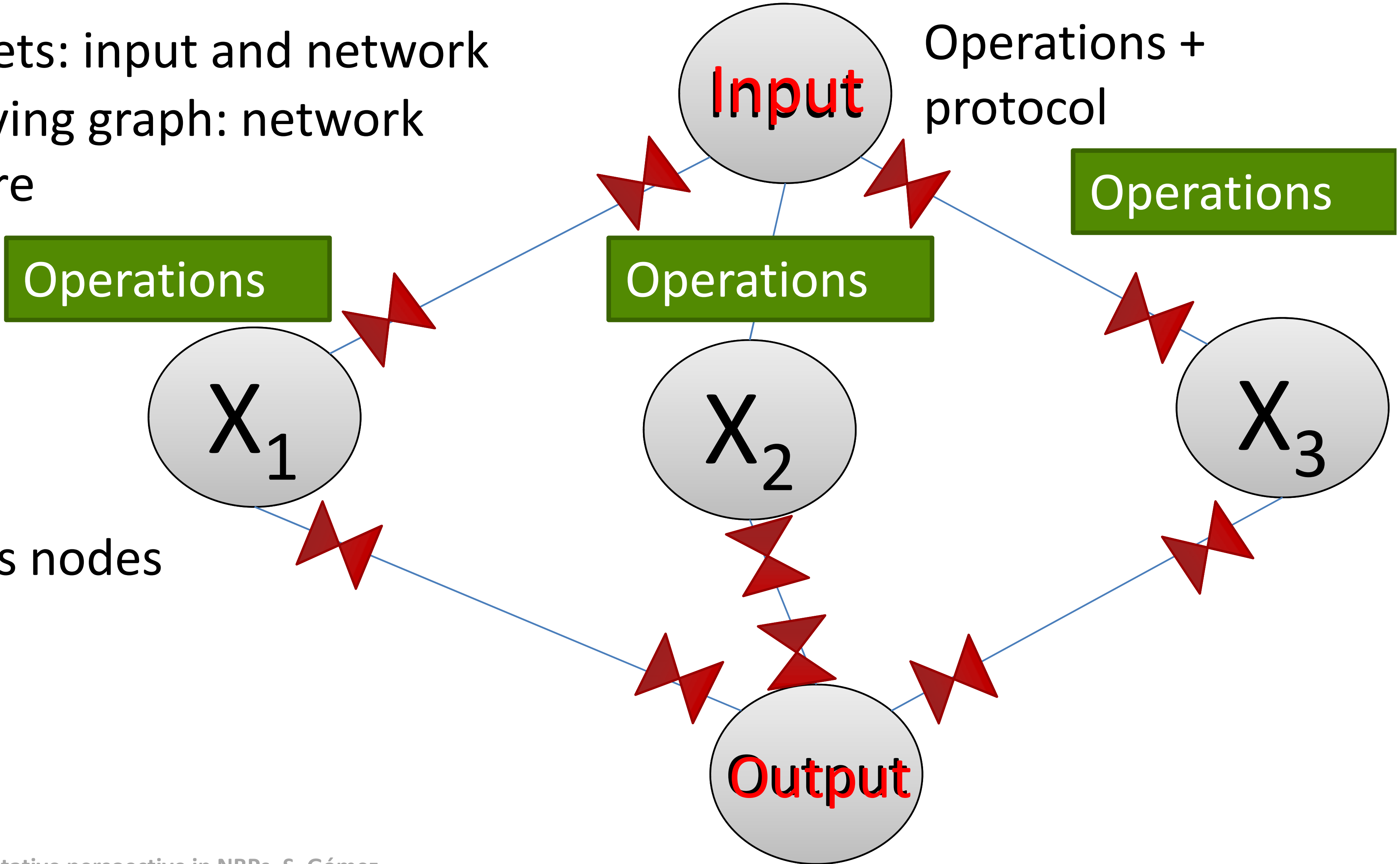
- Processors as generating languages devices
- Located in nodes of a network
- Data processing (as ADN strings) based on rewriting rules of a grammar
- Protocol Communication in the connections between nodes
- Parallelism in the processing and the communication phases

NBP model

Alphabets: input and network

Underlying graph: network structure

Operations + protocol

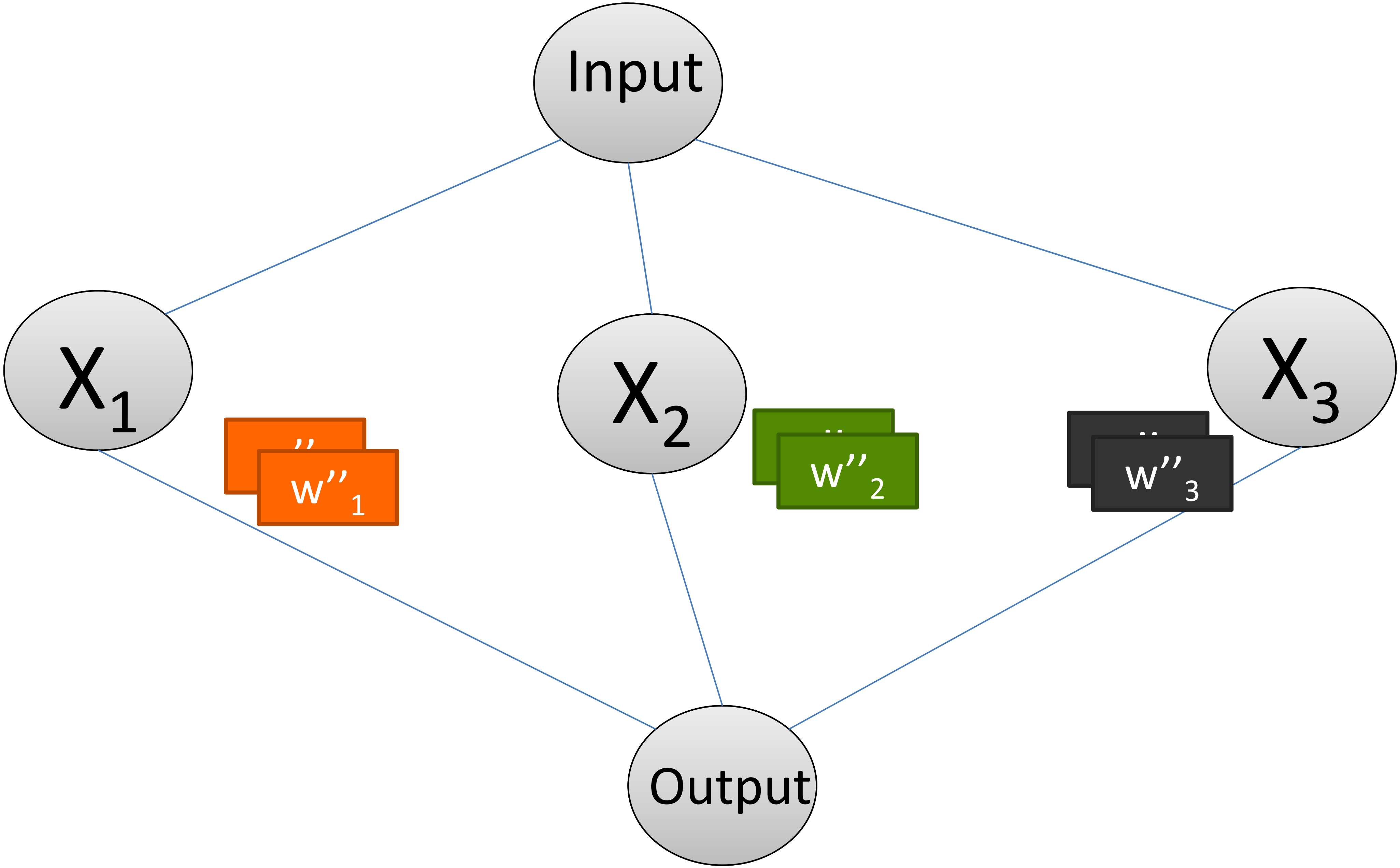


Processors nodes

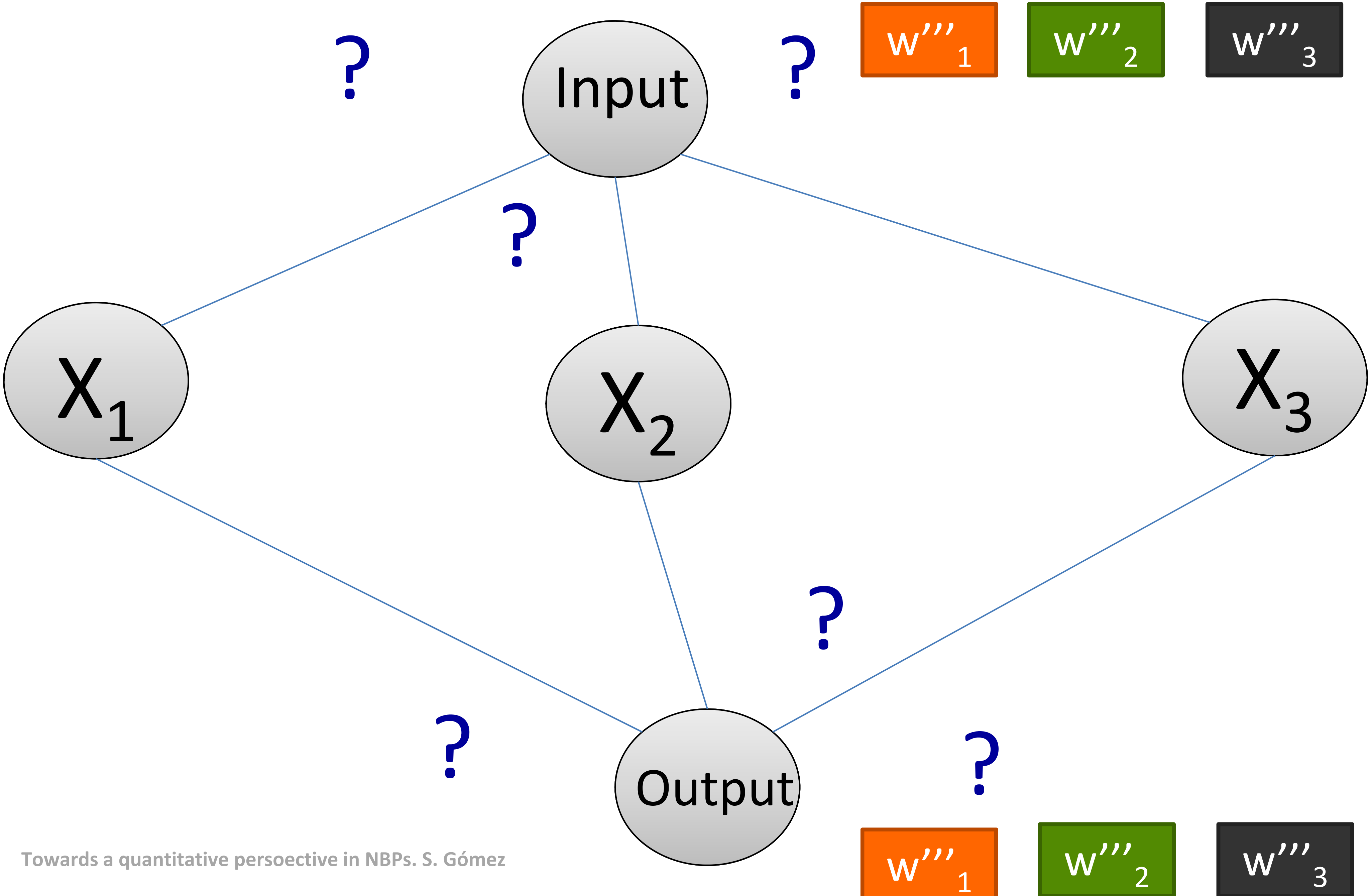
Objetivos, justificación y motivación

- Acercamiento a la realidad biológica
- Orientación a un carácter cuantitativo
- Cambio en el enfoque del dominio de los problemas

NBP Metamodel Dynamic



NBP Metamodel Dynamic



NBP Metamodel Dynamic
Formal definitions

***Γ* configuration** : $C\!: X_G \rightarrow 2^{V^*}$

Initial Γ configuration in $w \in V^*$

$$C_0^{(w)}(X_I) = \{w\} \text{ y } C_0^{(w)}(x) = \emptyset \;\; \forall x \in X_G - \{X_I\}$$

Evolution step

$$C \Rightarrow C' \; sii$$

$$C'(x) = M_x^{\alpha(x)}(C(x)) \; \forall x \in X_G$$

Communication step

$$C \vdash C' \; sii$$

$$C'(x) = \left(C(x) - \tau_x(C(x))\right) \cup \bigcup_{\{x,y\}\in E_G} \left(\tau_y(C(y)) \cap \rho_x(C(y))\right)$$

NBP Metamodel Dynamic Formal definitions

***Γ* Computation** in $w \in V^* : C_0^{(w)}, C_1^{(w)}, C_2^{(w)} \ldots,$

$$C_{2i}^{(w)} \Rightarrow C_{2i+1}^{(w)} \text{ y } C_{2i+1}^{(w)} \vdash C_{2i+2}^{(w)} \; \forall\, i \geq 0$$

A **computation** halts :

i. X_O is non-empty : *acceptation computation.*

ii. There are two identical configurations obtained in consecutive steps

Accepted langüge by Γ is

$L(\Gamma) =$

$\{ w \in V^* | \, \Gamma \; computation \; in \; w \; accepting \; computation\}$

NBP model claqssification

Type of operation

- Evolutionary
- Splicing
- Genetic

Filtering strategy

- I/O predicates
- Polarization

Type of data

- Strings
- Pictures

Evolutionary

Polarized Evolutionary

Networks of Evolutionary Processors: NEP

Networks of Evolutionary Processors: NEP

- **Evolutionary rule**: point mutations in a DNA sequence (insertion, deletion or substitution of a pair of nucleotides).
- $\boldsymbol{\sigma}: \boldsymbol{a} \rightarrow \boldsymbol{b}$ such that $a, b \in V \cup \varepsilon$
- Action rule: $\alpha = \{*, l, r\}$

Evolutionary rule σ	Definition	Action rule σ
Substitution	$a, b \neq \varepsilon$	$\alpha = \{*\}$
Deletion	$a \neq \varepsilon$ y $b = \varepsilon$	$\alpha = \{*, l, r\}$
Insertion	$a = \varepsilon$ y $b \neq \varepsilon$	

- Sub_V, Del_V e Ins_V set of all rules over V

Networks of Evolutionary Processors: NEP

- Filtering strategy: $\beta \in \{s, w\}$
  - s : *strong*
  - w: *weak*

- Set of permitting/forbidding symbols

Symbols	Input	Output	Strong	Weak
Permitting	PI	PO	All	1 or more
Forbiddibg	FI	FO	None	None

Networks of Evolutionary Processors: NEP

Definition: Evolutionary processor associated to the node x is a 5-tuple $(M_x, PI_x, FI_x, PO_x, FO_x)$ where:

- M_x is a finite set of evolutionary rules such that tal que $M_x \subseteq Sub_V$, $M_x \subseteq Del_V$ or $M_x \subseteq Ins_V$
- PI_x , FI_x are the permitting/forbbiding contexts/symbols respectively, such that $PI_x \cap FI_x = \emptyset$
- PO_x , FO_x are the permitting/forbbiding contexts/symbols respectively, such that $PO_x \cap FO_x = \emptyset$

Networks of Evolutionary Processors: NEP

Networks of Evolutionary Processors – NEP is a 8-tuple $(V, U, G, N, \alpha, \beta, X_I, X_O)$

- V, U tal que $V \subseteq U$
- $G = (X_G, E_G)$ **underlying graph.**
- $N: X_G \rightarrow EP_U$ mapping $x \in X_G$ with $\mathrm{N(x)} = (M_x, PI_x, FI_x, PO_x, FO_x)$
- $\alpha : X_G \rightarrow \{*, l, r\};\ \alpha(x)$
- β: $X_G \rightarrow \{s, w\}$ I/O filters
- X_I, X_O are input and output nodes

Polarized NEP

Polarized NEP

- Networks of Polarized Evolutionary Processors – NPEP [Mitrana,2012].
- **Polarization:** filter strategy.

Sign={-,0,+}

- **Valuetion mapping** for strings.
- **Filtering protocol**: **sign** of the word **but does not** real numeric value.
- Simulates cellular communication by ion channels

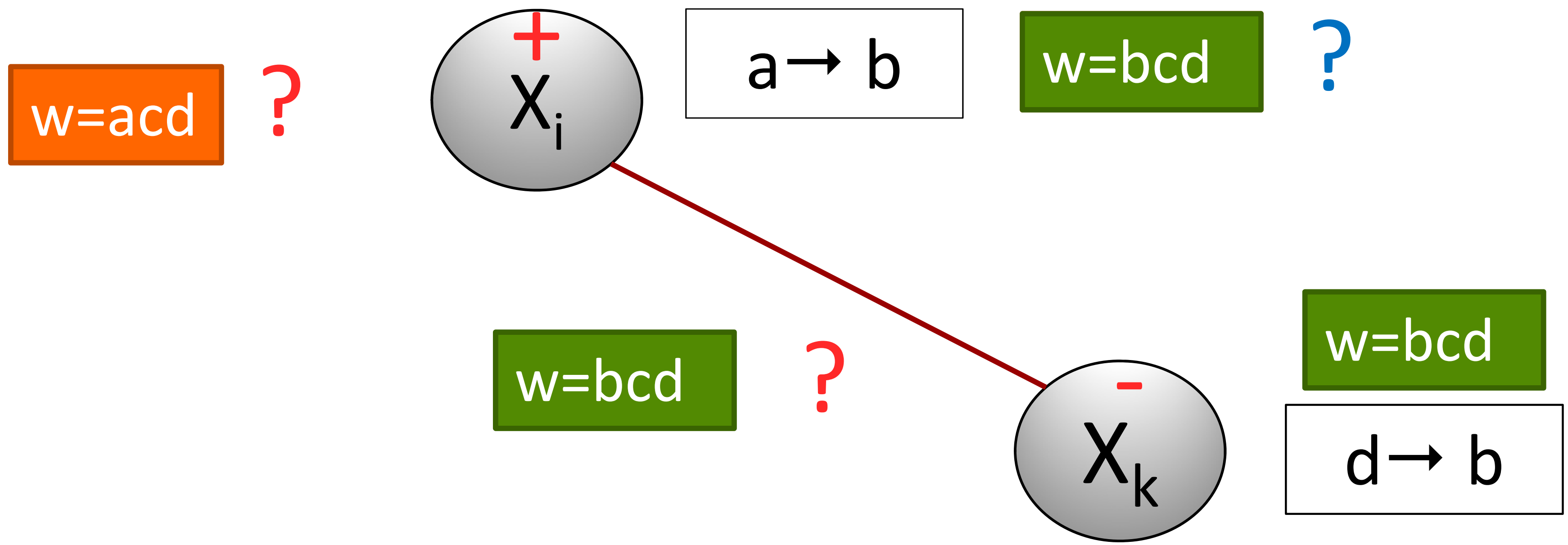
Polarized NEP

- Valuation function: φ de U^* en $\mathbb{Z}$

U={a,b,c}

φ(a)= 1	φ (b)=-1

- Polarity (sign) to each node



Polarized NEP

Prolarized Evolutionary Processor over V is a pair (M, α):

- $M \subseteq Sub_V$, $M \subseteq Del_V$ or $M \subseteq Ins_V$
- $\alpha \in \{-, 0, +\}$ is the node polarity

NPEP is a 7-tuple $\boldsymbol{\Gamma = (V, U, G, N, \varphi, X_I, X_O)}$ where

- $V, U, V \subseteq U$
- $G = (X_G, E_G)$ underlying graph
- $N: X_G \rightarrow EP_U$ is a mapping from $x \in X_G$ to $\mathrm{N(x)} = (M_x, \alpha_x)$
- φ is a valuation from U^* to $\mathbb{Z}$
- X_I, X_O are the input and outpu nodes respectively

Polarized NEP Dynamics

Γ **Configuration** = NEP model

Γ **Initial configuration** = NEP model

Evolutionary step

$$C \Rightarrow C' \text{ sii}$$

$$C'(x) = M_x(C(x)) \; \forall x \in X_G$$

Communication step

$$C \vdash C' \text{ sii}$$

$$\mathrm{C}(x) = (C(x) \setminus \{w \in C(x) | \, \varphi(w) \neq \alpha_x\})$$

$$\cup \bigcup_{\{x,y\} \in E_G} \left(w \in C(y) \middle| \alpha_y \neq \varphi(w) = \alpha_x\}\right) \; \forall x \in X_G$$

Computation = NEP

Qualitative or Quantitative aspects?

- NPEP is motivated by mathematical and computer science goals, but not necessarily by biological goals.
- Application of NEP in other differents domains
- It is necessary to consider not only their qualitative perspective but also the quantitative one.
- Quanitative aspects are a “sine qua non” condition within biological reality
- Although its true that NPEP incorporates a numerical evaluation over the data that processes, this is not used from quantitative perspective.

Quantitative NEPs

Quantitative NEPs

In cellular and biological phenomena:

- Compare software simulation vs experiments
- Quantitative valuations
  - Concentrations, gradients, thresholds, etc…
- It is necessary a NEP model with quantitative elements: **QNEPs**

Parametric NEP: PNPEP

- First model of the Quantitative NEP family.
- Polarized NEP extension
- Polarized NEP has a valuation mapping:
  - But it is only qualitative valuation.
- Now, we want to compute the exact weigth of valuation of a word

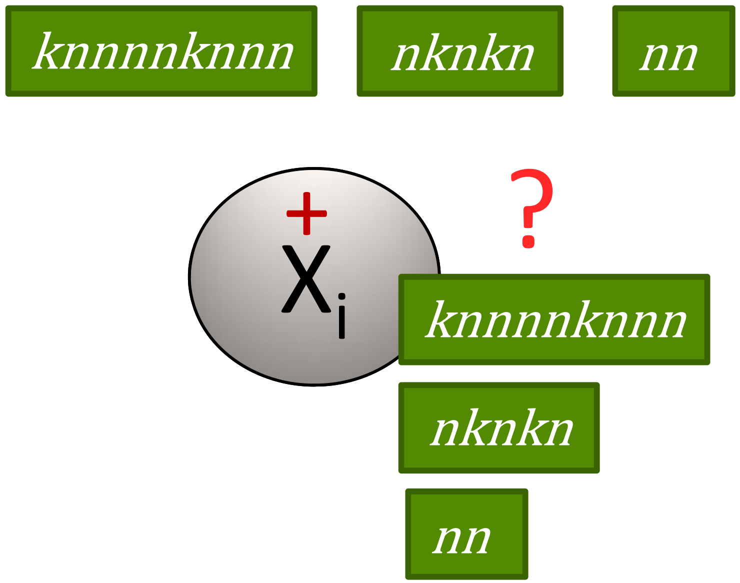
Parametric NEP: PNPEP

- In NPEP: φ is a valuation frome U^* to $\mathbb{Z}$
- If U={n,N,k,K,p}

φ**(n)= 1**	φ **(k)=-1**

Word	Mapping valuation	Polarity
nknkn	+	+
knnnnknnn	+	+
nn	+	+

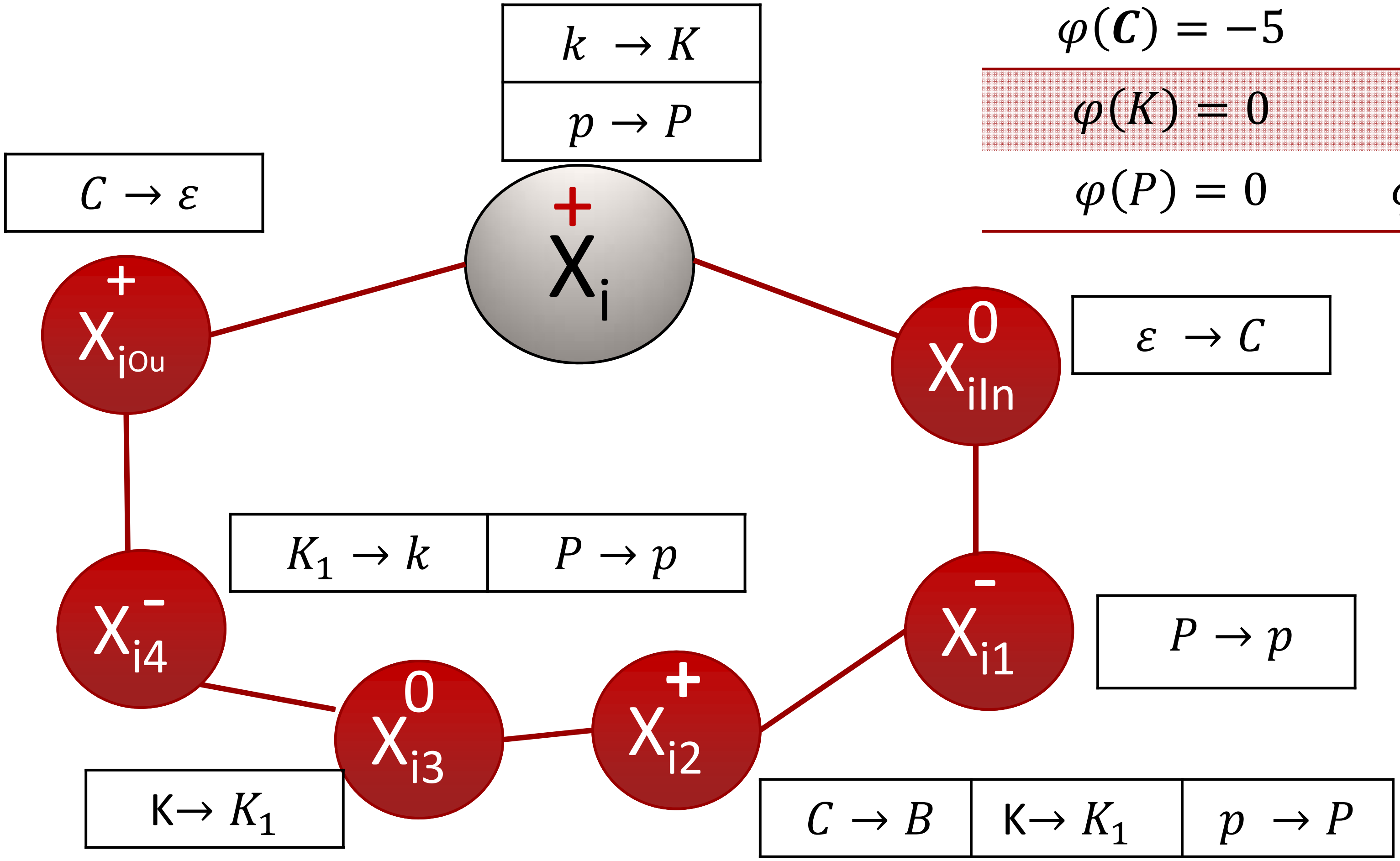
Word	Mapping valuation	Result
nknkn	+	1
knnnnknnn	+	5
nn	+	2



NPEP Valuation….

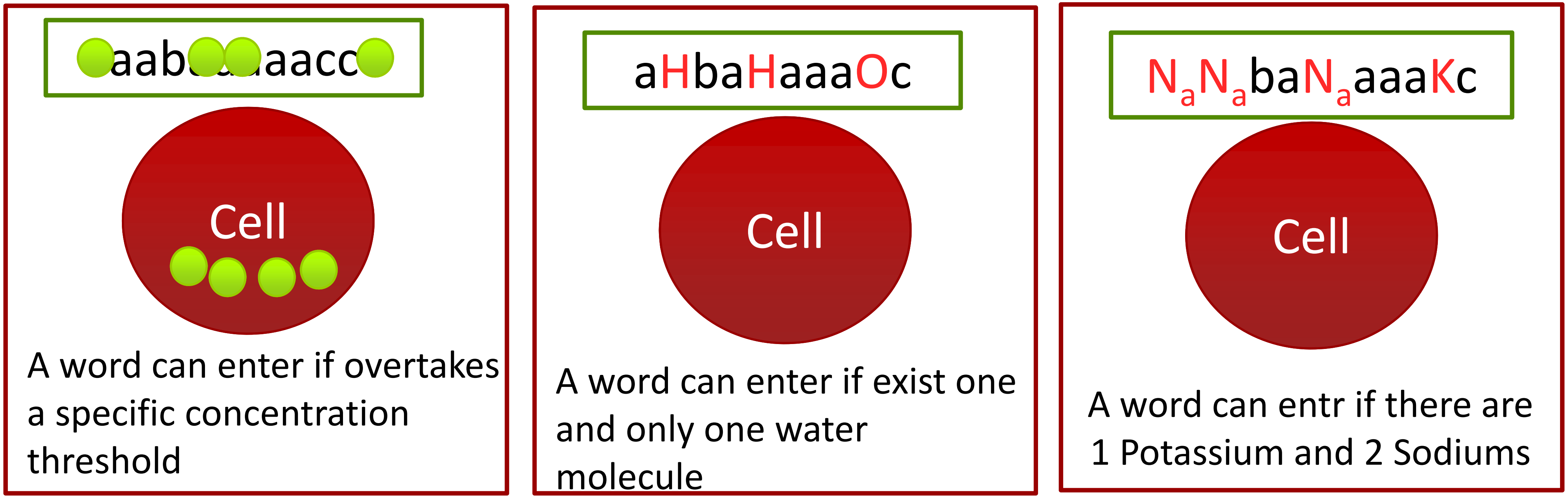
- **Must be filtering words having a concentration > 5 of symbols p**
  - To aggreegate symbols D,P,C,K,P in U alphabet

$\varphi(\boldsymbol{C}) = -5$	$\varphi(B) = 0$
$\varphi(K) = 0$	$\varphi(K_1) = 0$
$\varphi(P) = 0$	$\varphi(K_2) = -100$



Parametric NEP: PNPEP

- To fill this lack..

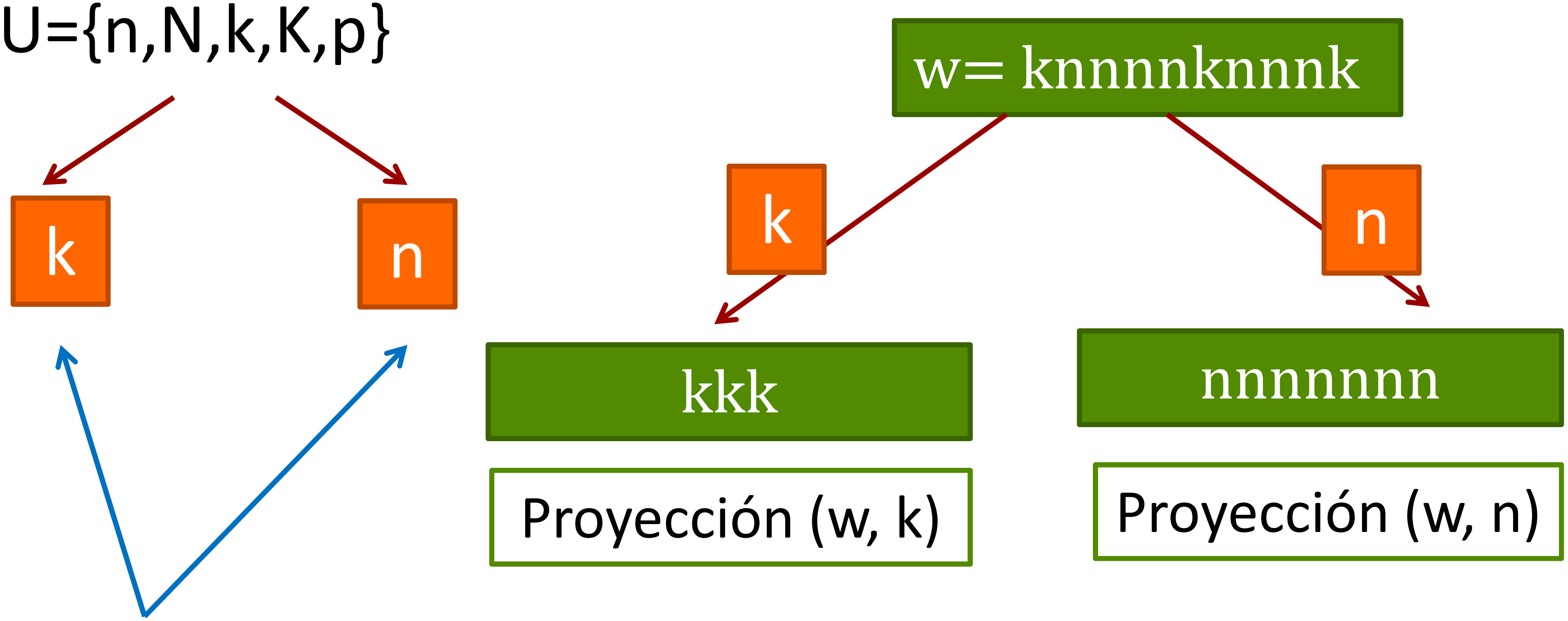


Parametric NEP: PNPEP

New elements:

- Projection function over words

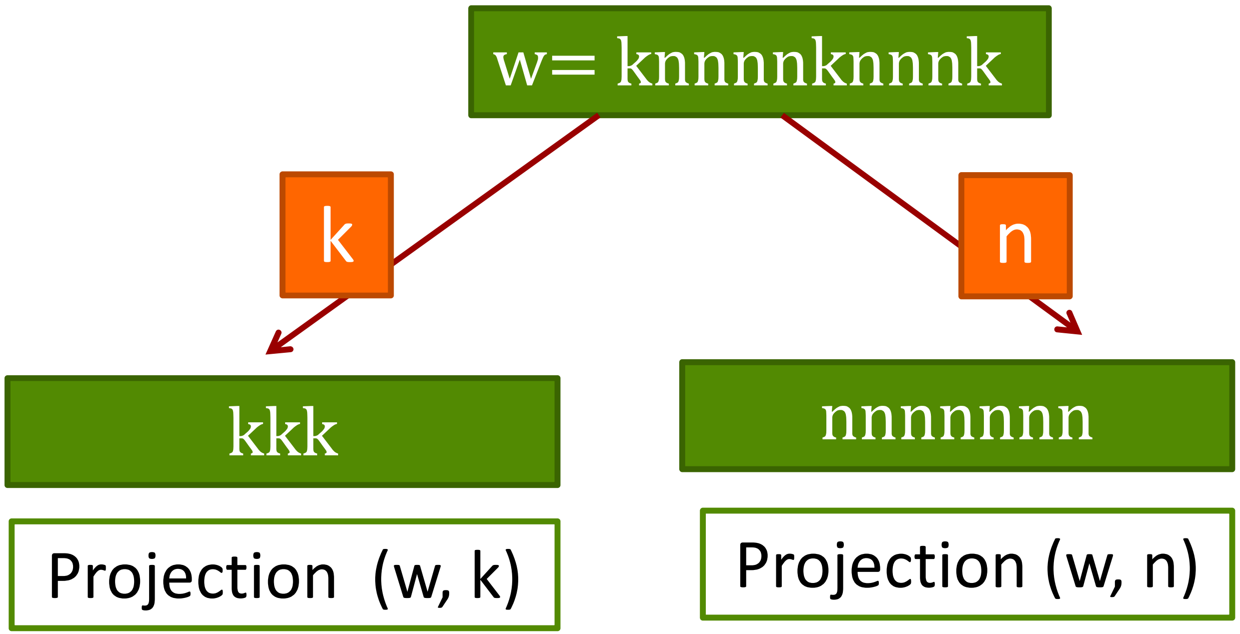
Si U={n,N,k,K,p}



It is necessary a set of partitions over U

Parametric NEP: PNPEP

- Evaluation of the projection over a specific interval



$5 \leq$ Potassium concentration ≤ 10 $\quad$ $100 \leq$ Soddiun comcentration≤ 200

Polarity is divided between less generic intervals

Parametric NEP: PNPEP

- Vualtion mapping NPEP is φ: $U^* \rightarrow \mathbb{Z}$
- **Redefining** $\boldsymbol{\varphi}$: $U^* \rightarrow \mathbb{Z}^m$
- If $2^U = P = \{P_1, P_{2,\ldots,} P_m\}$ then

$Projection\ function$:

$$\pi_j(w, P_j) = a'_1, a'_2, \ldots a'_k \qquad where\ a'_i \begin{cases} a_i\ if\ a_i \in P_j \\ \varepsilon\ otherwise \end{cases}$$

- If $\Pi = \{\pi_1, \pi_2, \ldots \pi_m\}$ then

$$\varphi(w) = \varphi_i(\pi_i(w, P_i)) \text{ for all } i \in \{1,2, \ldots m\}$$

Parametric NEP: PNPEP

- Polarized NEP: polarity denoted by $\alpha \in \{-, 0, +\}$
- New polarization: **labels for α**
  - Changing the notation: $\alpha \in \{(-\infty, 0), \{0\}, (0, +\infty)\}$
- Valuating the concentration of p ≥ 5 then
  - $\alpha \in \{(-\infty, 0), \{0\}, (0, 5), [5, +\infty]\}$

Classic notation	Parametric Polarized NEP
$\alpha \in \{(-\infty, 0), \{0\}, (0, +\infty)\}$ = $\alpha \in \{l_0, l_1, l_2\}$	$\alpha \in \{l_0, l_1, l_2 \dots l_m\}$ $\bigcup_{i=0}^{m} l_i = \mathbb{Z}$

Parametric NEP: PNPEP

- $\alpha \in \{(-\infty, 0), \{0\}, (0, 5), [5, +\infty)\}$

$w_1 =$ knnnnknnnk → 7

Projection (w_1,k): kkkkkkk

$w_2 =$ nknkn → 2

Projection (w_2,k): kk

$w_3 =$ nn → 0

Projection (w_3,k): ε

$$\alpha \in \{\underbrace{(-\infty, 0)}_{l_0}, \underbrace{\{0\}}_{l_1}, \underbrace{(0, 5)}_{l_2}, \underbrace{[5, +\infty)}_{l_3}\} = \{l_0, l_1, l_2, l_3\}$$

Parametric NEP: PNPEP

A **parametric polarized evolutionary processor** is a 3-tuple (M, S, α):

- $M \subseteq Sub_V$, $M \subseteq Del_V$ or $M \subseteq Ins_V$
- $S \subseteq \ P$ is the set of partitions of U that this processor evaluates
- $\alpha \in \{l_x^0, l_x^1, l_x^2, \dots l_x^m, \}$, m=card(S)

Is the polarity partition

Parametric NEP: PNPEP

Networks of Paramteric Polarized Evoltuionary Processors – PNPEP is a 8-tuple $\Gamma = (V, U, P, G, R, \varphi, X_I, X_O)$

- $V, U \ \ such\ that\ V \subseteq U$
- *P is a partition over U*
- $G = (X_G, E_G)$ is a underlying graph
- $N: X_G \ \rightarrow EP_U$ is the mapping form node to processors $\mathrm{N(x)} = (M_x, \mathrm{S}_x, \alpha_x)$
- $\varphi\ \ is\ \ a\ valuation\ from\ \ U^*\ \ to\, \mathbb{Z}^m$
- X_I, X_O are the input and output node respectively

Parametric NEP: PNPEP

V= {s, S,p,P, v, V,A} y ***U*** = {n,N, k,K, b,B, a, t, q, f,ñ}

$P = \{P_0 = \{n\}, P_1 = \{k\}, P_2 = \{K,N,K,g, B,a,q,f,ñ,t\}\}$

φ(p)= 1	**φ (k)=-1**

α Intervalo polarización	α_{x_i}	S
[0,5),[5,+∞)	$l_{xi}{}^{1}$	P_1

w_1= knnnnknnnk

kkkkkk

w_2=nknkn

w_3=nn

X_i

Parametric NEP: Dynamic

Γ **Configuration** = $C\colon X_G \rightarrow 2^{U^*}$

Γ **Initial configuration** = NPEP model

Evolutionary step

$$C \Rightarrow C' \text{ sii}$$
$$C'(x) = M_x(C(x))\ \forall x \in X_G$$

Communication step

$$C \vdash C' \text{ sii}$$

$$C'(x) = (C(x)\,\{w \in C(x)\,|\varphi_i(w) = \varphi(\pi_i(w)) \notin \alpha_{x,i} \forall\, \pi_i \in \Pi\,\} \cup \bigcup_{x,y \in E_G} (\{w \in C(y)|\varphi_i(w) = \varphi(\pi_i(w)) \in \alpha_{x,i} \exists\, \pi_i \in \Pi\})$$

Computation = NPEP

Na – K Pump simulation using Parametric NEP

Conceptos básicos

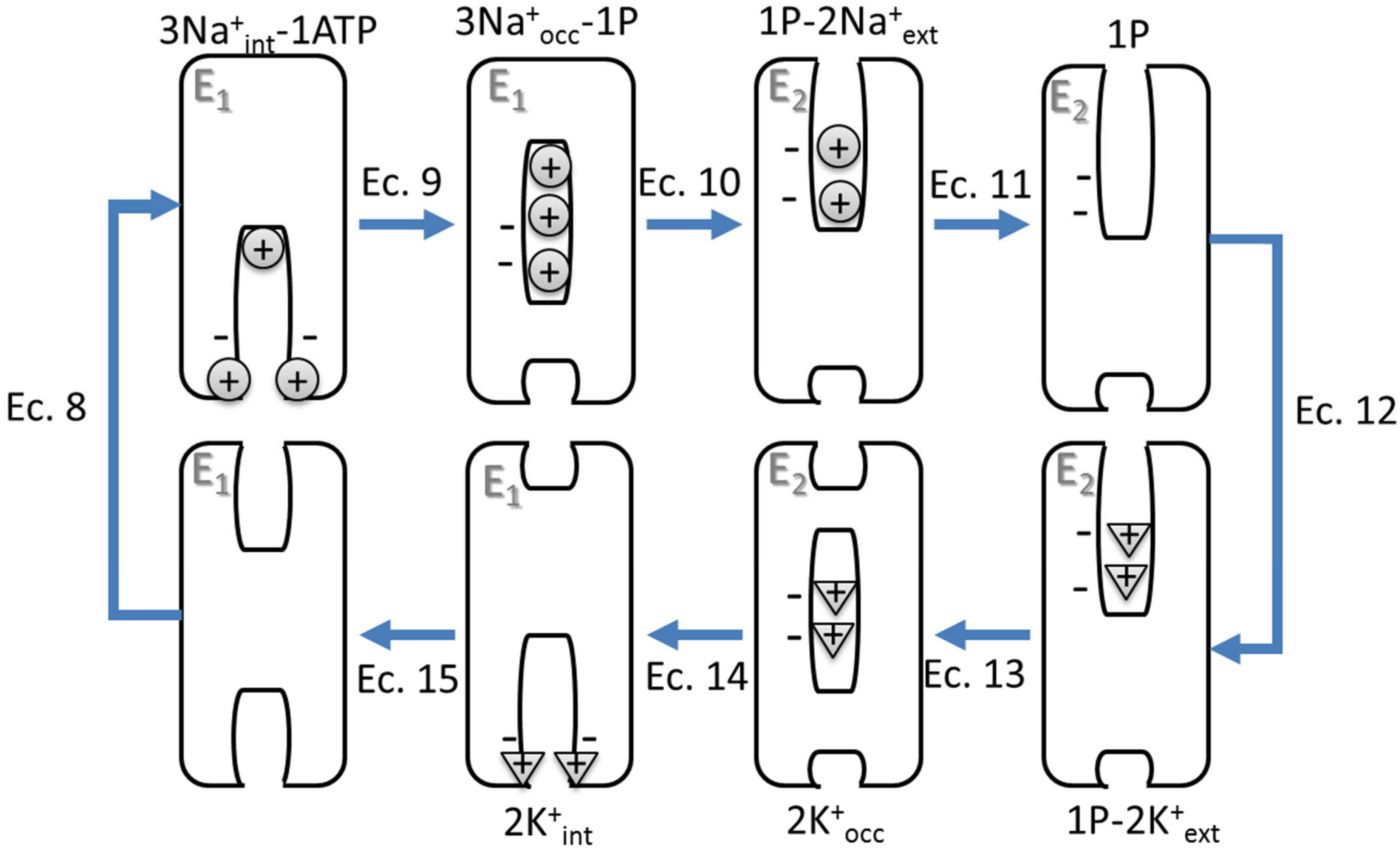
- **Sustancia química**: $a \in V$
- **Solución o entorno químico**: $w \in V^*$
- **Concentración de una sustancia**: $|w|_a, \ a \in V, \ w \in V^*$
- **Reacción química**: $R = \{\sigma_1, \sigma_2, \ldots, \sigma_n\}, n \in \mathbb{N}, \quad \sigma_i \in (Sub_V \cup Ins_V \cup Del_V)$
- **Estado del sistema** en un tiempo $i > 0$: $C_i(x)$ para todo $x \in X_G - \{X_I\}$

Simulating cellular transport with PNPEP

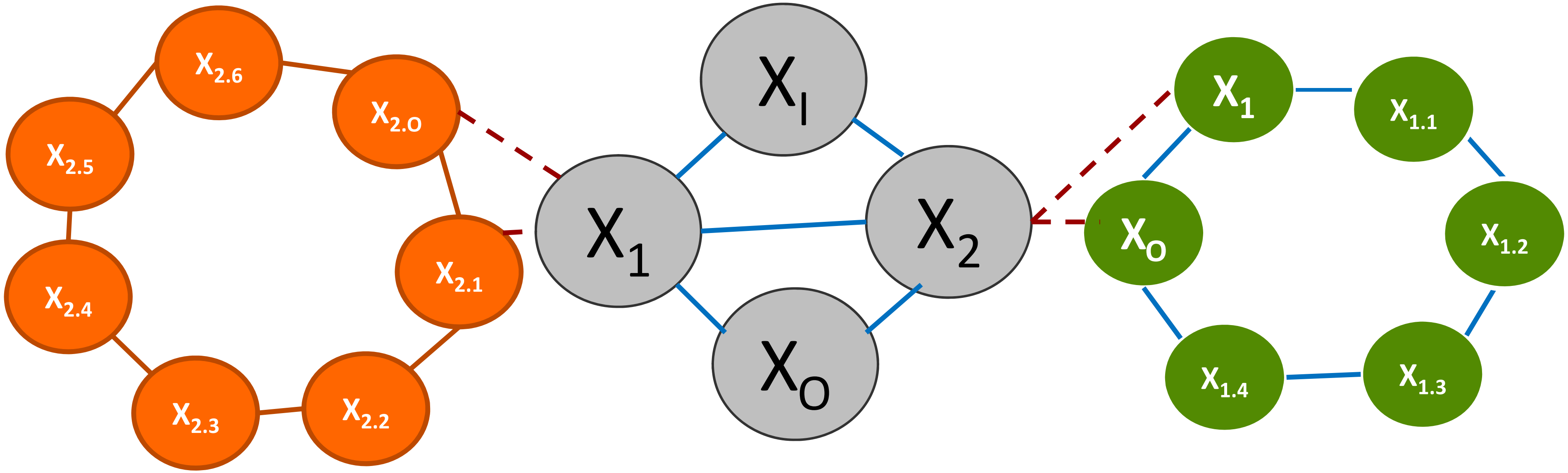
- Bomba Sodio-Potasio: transporte activo

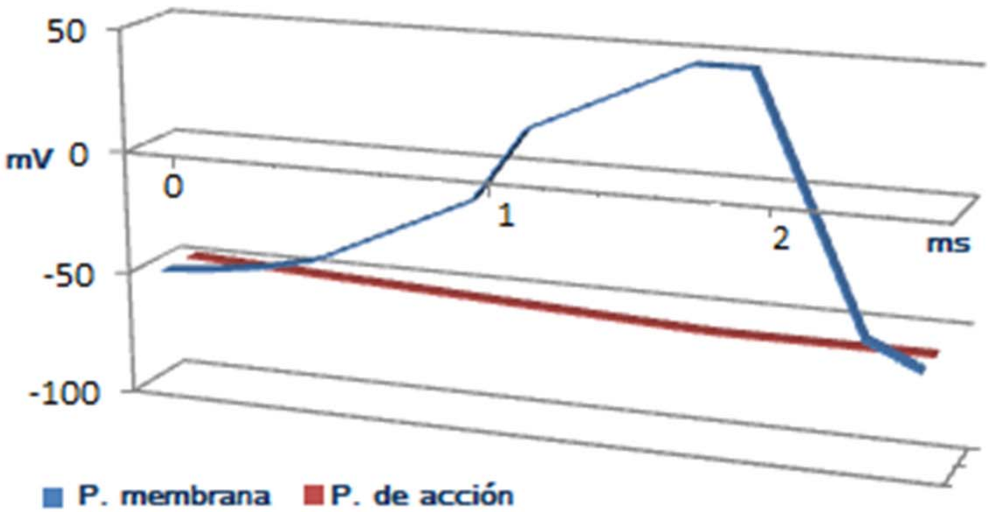
	Concentración extracelular	Concentración intracelular	Potencial reposo	Potencial reposo Células excitables
Na	145 mEq/L	[5; 15] mEq/L	-20mV -120mV	-70mV
K	5mEq/L	140 mEq/L		

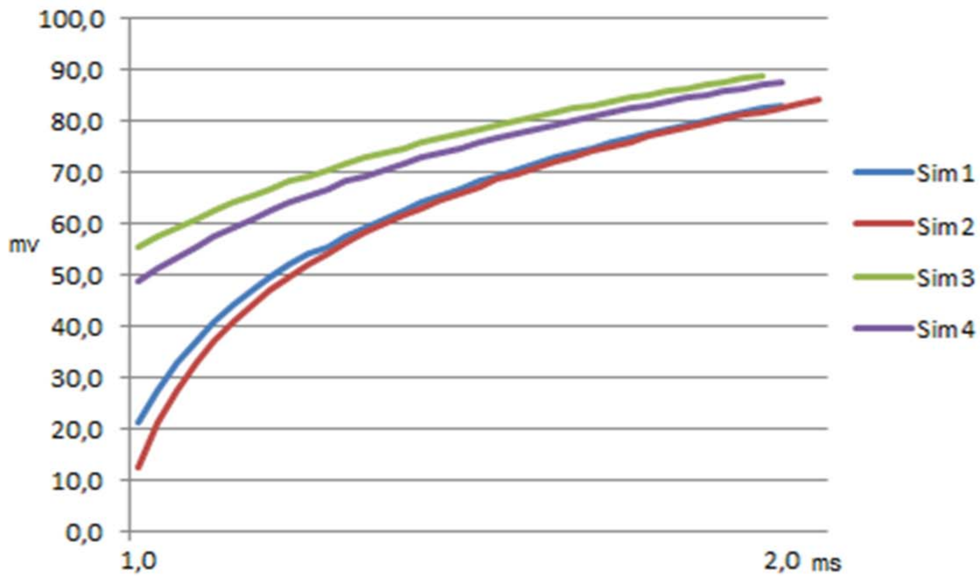
Simulating cellular transport with PNPEP



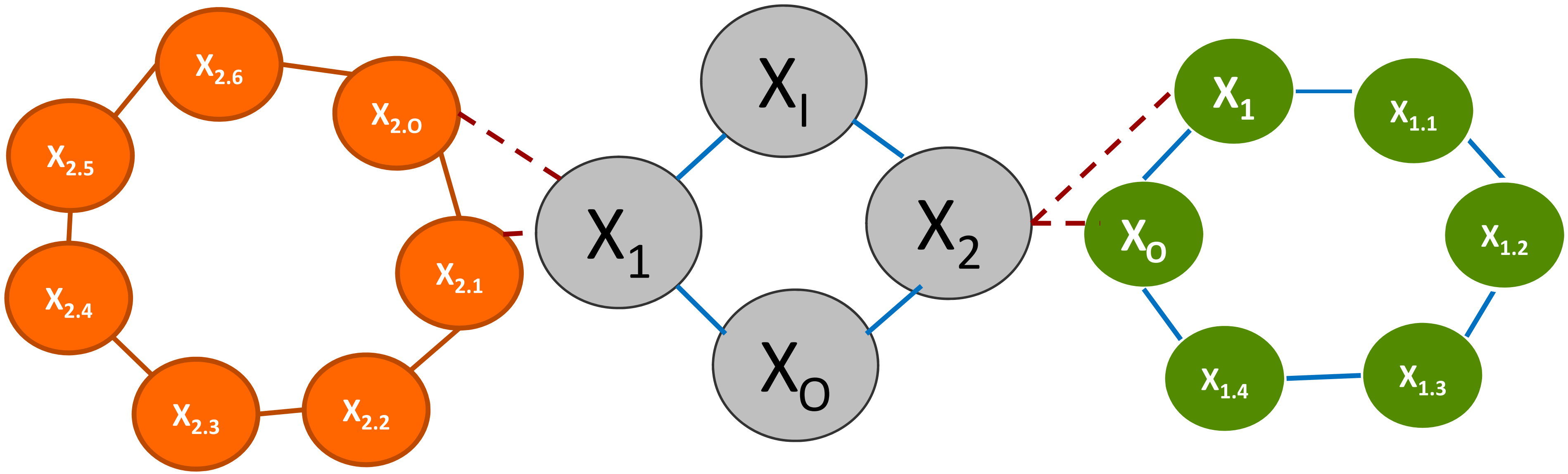
Simulating cellular transport with PNPEP

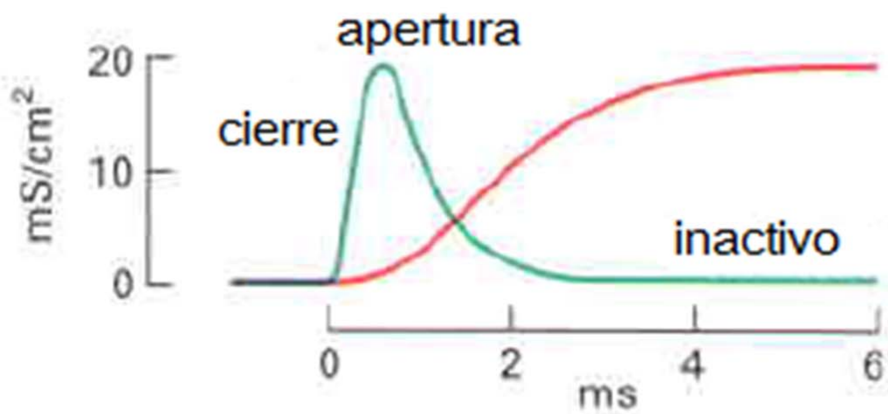


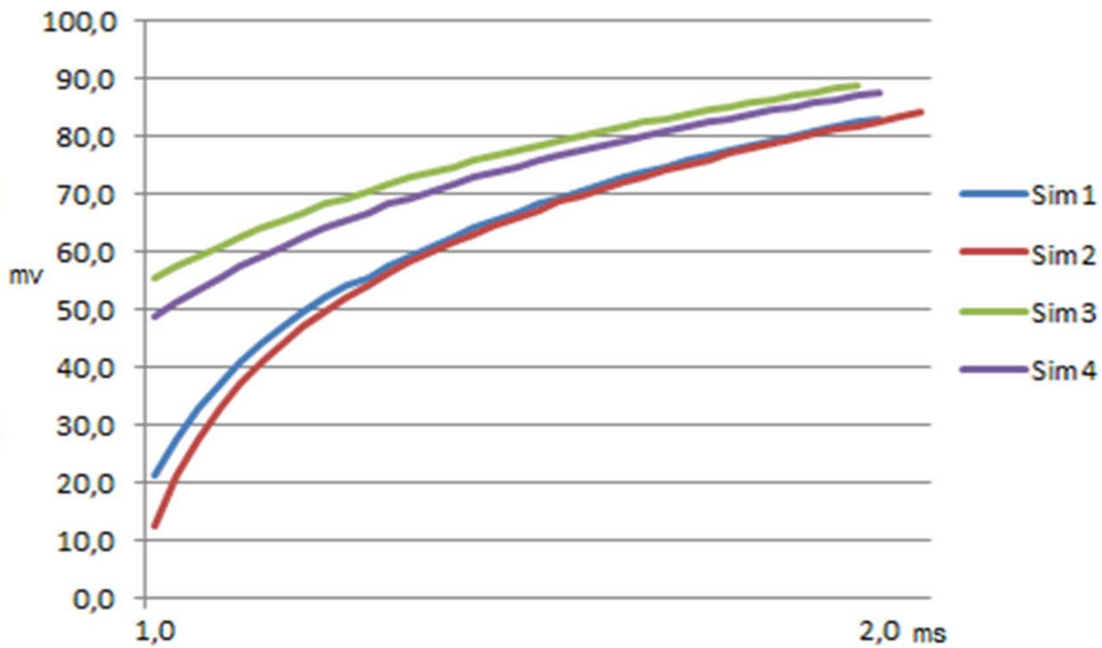




NPEP Paramétricas: Bomba Na-K







Open problems and future work

- PNPEP as a first model in a family of QNEPs - Quantitative NEPs,
  - Will may address probabilistic, estocastic, and more additional quantitative elements.
  - To study the dynamic of evoltuionary trajectory NEPs.
  - To calculate evolutionary distances
  - To classify and to distribute based on quantitative criterions
  - Behavior based on learning
  - To optimize based on multiobjetives

Thaks for your attention